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Evaluation of strength model parameters from Taylor impact tests

Julien Nussbaum*[a], Norbert Faderl[a]

[a] *French-German Research Institute of Saint-Louis, Saint-Louis F-68300, France*

Abstract

This paper provides a method to extract sets of parameters from Taylor impact tests [1]. The method consists in a two steps algorithm which associates a Monte-Carlo method to a Levenberg-Marquardt [2, 3] optimization loop, as proposed by Nistor [4]. Iteratively, the algorithm searches the set of constants that best fits the simulations to the experiments by minimizing the error between the data. The deformation of the cylinder is modeled by an axisymetric, two-dimensional model. Validation of the solver is performed by comparisons with ANSYS Autodyn simulations. We focus our study on the Johnson-Cook model [5]. First tests on the 6061-T6 aluminum and 4340 steel have shown good agreements. Some improvements are proposed.

Keywords : strength model, Johnson-Cook, Taylor test, Monte-Carlo, Levenberg-Marquardt, optimization

1. Introduction

Design of protections against ballistic threats requires simulations to reduce the costs of experimental campaigns. The dynamic behavior of materials is modeled by strength models implemented in the codes. The equations of these models need input constants that are in general not known and difficult to evaluate due to high strain rates involved in impact phenomena. In this work, we propose a method to extract such input parameters from experimental results obtained by Taylor impact tests [1]. This kind of dynamic tests are quite easy to perform and can reach strain rates ranges higher than with Hopkinson bars ($10^5 – 10^6$ s^{-1}). The idea is the following: an optimization loop tries to find the set of strength model parameters that minimizes the error between the experimental and computed results. Iteratively, the algorithm simulates a

* Corresponding author: Tel.: +33(0)389695157; fax: +33(0)389695359
E-mail address: julien.nussbaum@isl.eu

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set of experiments with different parameters and compares the calculated final length and mushroom diameter to the measured ones. The best combination of parameters is the one that gives the lowest error.

Nomenclature

σ_0	yield stress
A	basic yield stress at low strains
B	strain hardening constant
G	strain rate constant
n	strain hardening exponent
m	thermal softening exponent
ε_p	equivalent plastic strain
ε_p^*	normalized equivalent plastic strain rate
T_H	homolgous temperature
ψ_{ave}	averaged error function
L_f	final length of the cylinder
D_f	final mushroom diameter of the cylinder
C	calculated value
M	measured value
N	number of experiments

2. Optimization loop

In this part, the concept of the algorithm is briefly described. The challenge is to solve an inverse problem: from a database of Taylor impact tests results, we would like to find the strength model parameters of the tested material in order to accurately simulate these experiments with a hydrodynamic code. Actually, we focus the study on the Johnson-Cook model [5] which expresses the yield stress σ_0 as

$$\sigma_0 = \left(A + B\,\varepsilon_p^n\right)\left(1 + G\log\varepsilon_p^*\right)\left(1 - T_H^m\right) \quad (1)$$

where A, B, G, n and m are the materials parameters, ε_p is the equivalent plastic strain, ε_p* is the

dimensionless plastic strain rate and T_H is the homologous temperature. For each material, five unknown parameters have to be determined in the space of solutions. The dimensions of this space are determined by the minimum and maximum value for each parameter, defined by the user.

In order to fit the simulations results to the experimental observations, we propose to iteratively search the set of parameters that minimizes the averaged error function ψ_{ave} defined in [6] as

$$\psi_{ave} = \frac{1}{2N}\sum_{k=1}^{N}\sqrt{\left(\frac{L_{f,k}^{C}-L_{f,k}^{M}}{L_{f,ave}^{M}}\right)^{2}+\left(\frac{D_{f,k}^{C}-D_{f,k}^{M}}{D_{f,ave}^{M}}\right)^{2}} \tag{2}$$

where the superscripts C and M correspond respectively to the calculated and measured values. The final length of the cylinders is noted L_f and the final mushroom diameter D_f. The subscript *ave* corresponds to the averaged value over the N tests in the database.

The averaged error function is very complex and can not be analytically expressed in function of the five parameters. We can only search numerically a minimum in the space of solutions without knowing whether it is a local or a global minimum. As in [4], the optimization algorithm uses the Levenberg-Marquardt method ([2], [3]) in order to find the local minimum of ψ_{ave} in the neighborhood of a starting point. This starting point is determined during a first step by a Monte-Carlo method which scans randomly the space of solutions. The selected point is the one that presents the lowest averaged error.

3. Results

For the first tests, we used experimental results from the literature [7, 8]. In order to validate the algorithm, single simulations on the well-known materials 4340 steel and 6061-T6 aluminum were performed and the computed results were compared to the experimental results with a given set of parameters for the Johnson-Cook strength model. These materials were chosen as reference for validation because they present two different equations of state (linear and Mie-Grüneisen) which were implemented in the code. In order to strengthen the validation, our numerical results were compared to the results obtained with the ANSYS Autodyn commercial code on the same simulations. Once the numerical core of the code was validated, complete optimization loops were performed on the two same materials, where the strength model parameters were considered as unknown.

3.1. Evaluation of the parameters for the 6061-T6 aluminum

For this materials, the data found in [5] were used as initial parameters for the Johnson-Cook model and in [9] for the Mie-Grüneisen equation of state (shock). Eleven experiments from [7] were used as the database for the optimization loop. The maximum number of iterations for the Monte-Carlo method was set to 3000. The initial parameters from the literature, the dimensions of the solutions space and the solution given by the optimization loop are synthesized in the table 1.

The same eleven simulations were performed with the two sets of parameters on both codes. The figure 1 represents the error between the calculated and measured data for each test. The table 2 presents the averaged errors in function of parameters and code. The ISL code gives in general better results with both parameters than the ANSYS Autodyn code, validating the numerical solver. By comparing the

simulations with the two sets of parameters, one can observe that the averaged errors decrease for both codes with the new parameters. The solution of the optimization algorithm is then in good agreement with the material properties.

Table 1. 6061-T6 aluminum – initial strength model coefficients and solution with min and max boundaries

Parameter	Initial value	Min value	Solution	Max value
Yield stress A (kPa)	$3.24\ 10^5$	$2.5\ 10^5$	$3.47\ 10^5$	$4\ 10^5$
Hardening constant B (kPa)	$1.14\ 10^5$	$5\ 10^4$	$1.11\ 10^5$	$2\ 10^5$
Hardening exponent n (-)	0.42	0.35	0.37	0.5
Strain rate constant G (-)	0.002	0.001	0.0019	0.003
Thermal softening exponent m (-)	1.34	1.2	1.24	1.4

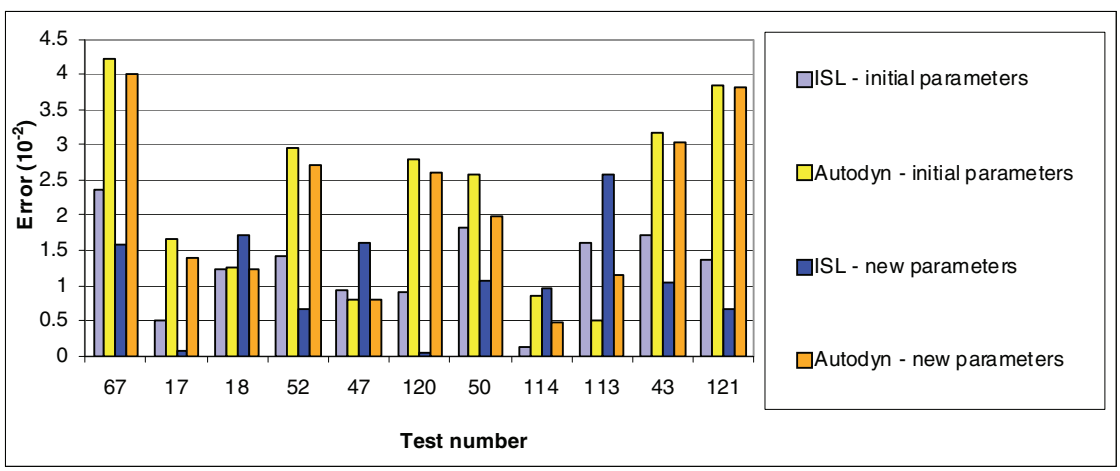

Fig. 1. 6061-T6 aluminum – comparison of errors per experiments for both sets of parameters.

Table 2. 6061-T6 aluminum – averaged errors for both sets of parameters

Code	Averaged error with the initial parameters	Averaged error with the new parameters
ISL	$1.40\ 10^{-2}$	$1.18\ 10^{-2}$
Autodyn	$2.29\ 10^{-2}$	$2.12\ 10^{-2}$

3.2. Evaluation of the parameters for the 4340 steel

For the second test, the 4340 steel was studied with a linear equation of state. The materials data were found in the literature [10]. Here again, the experimental results are taken from the literature [8]. The number of iterations for the Monte-Carlo method was set to 10^5. The initial parameters from the literature, the dimensions of the solutions space and the solution given by the optimization loop are synthesized in the table 3.

Table 3. 4340 steel - – initial strength model coefficients and solution with min and max boundaries

Parameter	Initial value	Min value	Solution	Max value
Yield stress (kPa)	$7.92\ 10^5$	$6\ 10^5$	6.2110^5	$9\ 10^5$
Hardening constant (kPa)	$5.1\ 10^5$	$4\ 10^5$	$5.94\ 10^5$	$6\ 10^5$
Hardening exponent (-)	0.26	0.2	0.284	0.3
Strain rate constant (-)	0.014	0.01	0.018	0.02
Thermal softening exponent (-)	1.03	1	1.004	1.1

The averaged errors for both codes and sets of parameters are synthesized in the table 4. The results are promising because the averaged errors remain limited in all cases (comparable to the aluminum test), but the error with the ANSYS Autodyn code significantly increases with the new set of parameters. This behavior was not observed in the case of the aluminum. Complementary tests have to be performed.

Table 4. 4340 steel – averaged errors for both sets of parameters

Code	Averaged error with the initial parameters	Averaged error with the new parameters
ISL	$2.00\ 10^{-2}$	$1.98\ 10^{-2}$
Autodyn	$1.66\ 10^{-2}$	$2.10\ 10^{-2}$

4. Conclusions and outlooks

In this paper, an optimization algorithm was described which extracts a set of parameters for the Johnson-Cook strength model from Taylor impact tests. Two different materials were studied (4340 steel and 6061-T6 aluminum). The optimization loop associates a Monte-Carlo method as a first step with the Levenberg-Marquardt method as the second step. After choosing randomly the parameters in the ranges given by the user, the code simulates the impacts of cylinders on a rigid anvil, according to experimental tests. This step is repeated several times. The selected set of parameters is the one which minimizes the

error between the computed and experimental results. These parameters are then considered as the initial point of the Levenberg-Marquardt algorithm, which iteratively adapt the parameters to approach the local minimum of the error function in the neighborhood of the initial point.

The first tests presented in this paper were performed on the well-known 4340 steel and 6061-T6 aluminum. Despite the fact that the strength model parameters are known for these two materials, we considered them as unknown and let the optimization loops search a solution. Simulations of some Taylor impact tests were then performed with our code and the ANSYS Autodyn commercial code. For both materials, the numerical results with the solution given by the optimization loop were in good agreement with experiments.

Several tests still have to be performed to completely validate the algorithm. For the optimization loop, other error functions will be put on test to study their influence on the results. Because only relatively small solutions spaces have been used, some tests with wider ones will be performed. The final tests will be the simulations of various projectiles impacts on targets in 6061-T6 aluminum or 4340 steel and the comparison with experimental results.

This work is only a basis for a more ambitious program. Many improvements can be made to enhance the algorithm. First of all, the parallelization of the algorithm on multi-processors devices will reduce significantly the computing costs and enable the use of a number of iterations higher in the optimization loop. Then, the integration of high speed camera in the experimental set-up could give some interesting information on the cylinder's deformation during the impact, which can be exploited by the algorithm to perform some intermediate comparison between experimental and numerical results. At last, complementary strength models and failure model will be implemented to increase the potential of the code.

References

[1] Taylor GI. The use of flat-ended projectiles for determining dnamic yield stress: I. Theoretical considerations. *Proc Royal Soc Lond Ser A* 1948;**194**:289-300.

[2] Levenberg K. A method for the solution of certain non-linear problems in least squares. *Quarterly of Applied Math* 1944;**2**(2):164-168.

[3] Marquardt DW. An algorithm for the least-squares estimation of nonlinear parameters. *SIAM J of Appl Math* 1963;**11**(2):431-441.

[4] Nistor I. Identification expérimentale et simulation numérique de l'endommagement en dynamique rapide : application à l'aéronautique. *PhD Thesis IBPT, France*; 2005.

[5] Johnson GR, Cook WH. A constitutive model and data for metals subjected to large strains, high strain rates, and high temperatures. *Proc 7th Int Symp on Ballistics, The Hague*; 1983.

[6] Rule WK. A numerical scheme for extracting strength model coefficients from Taylor test data. Int J Impact Engng 1997;**19**(9-10):797-810.

[7] House JW. Taylor Impact Testing. *Report AFATL-TR-89-41 Air Force Armament Lab*; 1989.

[8] Wilson LL, House JW, Nixon ME. Time resolvable deformation from cylinder impact test. *Report AFATL-TR-89-76 Air Force Armament Lab*; 1989.

[9] Steinberg DJ. Equation of state and strength model properties of selected materials. *LLNL*; 1991.

[10] Johnson GR, Cook WH. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. *Engng Frac Mech* 1985;**21**(1):31-48.